Exploitation of Environmental Complexity in Shallow Water Acoustic Data Communications

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LONG-TERM GOALS

Conduct feasibility experiments and associated algorithm design to explore how complexity of the shallow water acoustic environment can be used advantageously in acoustic data communications.

OBJECTIVES

Exploit environmental complexity through both real and synthetic aperture spatial processing to mitigate multipath-related fading and intersymbol interference in acoustic data communications.

APPROACH

The origin of this research is our experience with carrying out ocean acoustic time reversal experiments over a broad range of frequencies. Through a series of experiments conducted jointly between MPL and the NATO Undersea Research Centre (NURC), we have demonstrated that complexity of the ocean environment fundamentally is advantageous and facilitates rather than inhibits the resolution of physical processes, detection of targets, and acoustic telemetry of data. Furthermore, the time reversal experiments have illustrated that the ocean maintains a far greater inherent coherence than previously has been thought possible. Thus, the overall goal of this research is to take advantage of the self-adaptive nature of the complex ocean environment and learn how to exploit fluctuations, scattering, and variability.

Multiple-Input / Multiple-Output (MIMO) Acoustic Data Communications

The active time-reversal approach directly achieves spatial diversity through use of an array of sources. Source array diversity can be complemented with receive array diversity to enable transmitting independent communication sequences in parallel thus increasing the total data rate through the channel. The source array and receive array pair implements a multiple-input/multiple-output (MIMO) system. Although not optimized for overall communication system performance, the time-reversal approach is straightforward, results in relatively compact two-way channel responses, and yields high SNR at the focal depths of the communication sequences. Furthermore, the simple strategy of post-processing the communication sequence observed at a focal depth with a single-channel equalizer can prove effective.

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Synthetic Aperture Acoustic Data Communications

Here our objective is to exploit the dynamic propagation complexity arising from source-receiver motion to achieve the equivalent of an extended physical aperture with a single source-receiver pair. The underlying approach involves using distributed aperture time reversal to compensate for channel dispersion and the resulting problem of intersymbol interference (ISI). In order to fully understand medium complexity in the role of enhancing construction of the synthetic aperture, the focal region structure and temporal sidelobe characteristics obtained with a synthetic aperture array in the ocean medium needs to be explored. In addition, since we typically record transmissions on a vertical receive array, a direct comparison can be made between the synthetic aperture approach to a single receive array element and passive time reversal where a single transmission is received on multiple receive array elements – as well as combinations of the two. Essentially, we will be investigating how the medium complexity maps into spatial diversity between the source and receive array.

WORK COMPLETED

Experimental data collected during a joint experiment with the NATO Undersea Research Centre (NURC) in 2005 has demonstrated the feasibility of multiuser communications using passive time reversal combined with a single channel decision feedback equalizer (DFE) after multichannel combining [7]. Data transmission was demonstrated between multiple users (sources) and a vertical receiving array at 4 km and 20 km ranges achieving an aggregate data rate of 6 kbits/s in both cases.

RESULTS

In active time reversal, the channel response $h_i^j(t)$ from each source (superscript j) in a source array to a desired focal point (subscript i) in the ocean is obtained, time reversed, and retransmitted simultaneously from all sources. In the context of acoustic data communications, the time reversed channel response is used as the symbol waveform onto which the data bits are phase (and amplitude in the case of QAM) encoded. Although the symbols are heavily overlapped at the source array, they compress nicely in both time and space at the focal point [1-3].

While active time reversal retransmits the time reversed channel response, passive time reversal (see Fig. 1) applies matched filtering at each receiver element (subscript i) with $h_i^j(-t)$ and combines them coherently across the M receiving elements for a given user (superscript j) [4, 6-8]. Knowledge of the channel responses is provided by a channel probe signal at the beginning of each data packet (e.g. a LFM chirp). Complexity of the channel is beneficial for time reversal communications yielding an aggregate response for each user after multichannel combining close to a delta function (expressed analytically as the summation of the autocorrelations of each channel impulse response and denoted by q(t) in [4,7]). After multichannel combining, each user signal is processed with a single channel decision feedback equalizer (DFE) to remove any residual intersymbol interference (ISI) and compensate for channel fluctuations during the packet transmission.

As part of FAF-05 (Focused Acoustic Fields Experiment 2005), a multiuser communications experiment using passive time reversal was conducted in a relatively flat region in 120 m deep water north of Elba Island off the west coast of Italy [7]. The 29-element source array (SRA) covered the water column from 34 m to 112 m. Multiple transmitters were selected from the SRA to represent users at different depths. The 32-element vertical receive array (VRA) was deployed at two different ranges (4 km and 20 km) north of the SRA and spanned the water column from 48 m to 110 m with 2 m spacing (see Fig. 2). The communications transmissions had a 1 kHz bandwidth at a center frequency of 3.5 kHz and a symbol rate of 500 symbols/s.

The channel responses measured between the source array transducer at 96 m depth (SRA Ch #7) and all receiving array hydrophones are illustrated in Fig. 3 when the VRA was deployed at 4 km range. The total spread is approximately 90 ms resulting in an ISI of 45 symbols. The scatter plots in Fig. 4 illustrate the receiver performance for 6 users all transmitting simultaneously using QPSK modulation and achieving an aggregate data rate of 6 kbits/s with almost no bit errors.

The VRA also was deployed at a range of 20 km. The channel responses measured between the source array transducer at 88 m depth (SRA Ch #10) and all receiving array hydrophones are illustrated in Fig. 5. As a consequence of the longer range, there are fewer significant modes (or rays) resulting in a delay spread of about 20 ms or 10 symbols. The scatter plots in Fig. 6 illustrate the receiver performance for 3 users using 16 QAM modulation. An aggregated data rate of 6 kbits/s also was achieved although with a larger number of bit errors.

IMPACT / APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA and NRL which are exploring various aspects of high frequency channel characterization with specific applications to acoustic data communications and includes experimental work with the NATO Undersea Research Centre (NURC) and the recent KauaiEx (2003) and Makai (2005) experiments.

PUBLICATIONS

[1] G.F. Edelmann, H.C. Song, S. Kim, W.S. Hodgkiss, W.A. Kuperman, and T. Akal, "Underwater acoustic communications using time reversal," J. Oceanic Engr. 30: 852-864 (2006). [published, refereed]

[2] H.C. Song, R. Roux, W.S. Hodgkiss, W.A. Kuperman, T. Akal, and M. Stevenson, “Multiple-input/multiple-output coherent time reversal communications in a shallow water acoustic channel,” IEEE J. Oceanic Engr. 31: 170-178 (2006). [published, refereed]

[3] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, M. Stevenson, and T. Akal “Improvement of time-reversal communications using adaptive channel equalizers,” IEEE J. Oceanic Engr. 31: 487-496 (2006). [published, refereed]

[4] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, W.J. Higley, K. Raghukumar, T. Akal, and M. Stevenson, “Spatial diversity in passive time reversal communications, J. Acoust. Soc. Am. 120: 2067-2076 (2006). [published, refereed]

[5] J.F. Sifferlen, H.C. Song, W.S. Hodgkiss, W.A. Kuperman, and M. Stevenson, “An iterative equalization and decoding approach for underwater acoustic communication,” IEEE J. Oceanic Engr. (submitted, 2006).

[6] H.C. Song, W.S. Hodgkiss, and S.M. Kim, "Performance prediction of passive time reversal communications (L)," *J. Acoust. Soc. Am.* 122(5): 2517-2518 (2007).

[7] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, T. Akal, and M. Stevenson, "Multiuser communications using passive time reversal," *IEEE J. Oceanic Eng.* (in press, 2007).

[8] H.C. Song, W.S. Hodgkiss, Aijun Song, and Mohsen Badiey, "Single channel passive time reversal communications with a moving source (L)," *J. Acoust. Soc. Am.* (submitted, 2007).

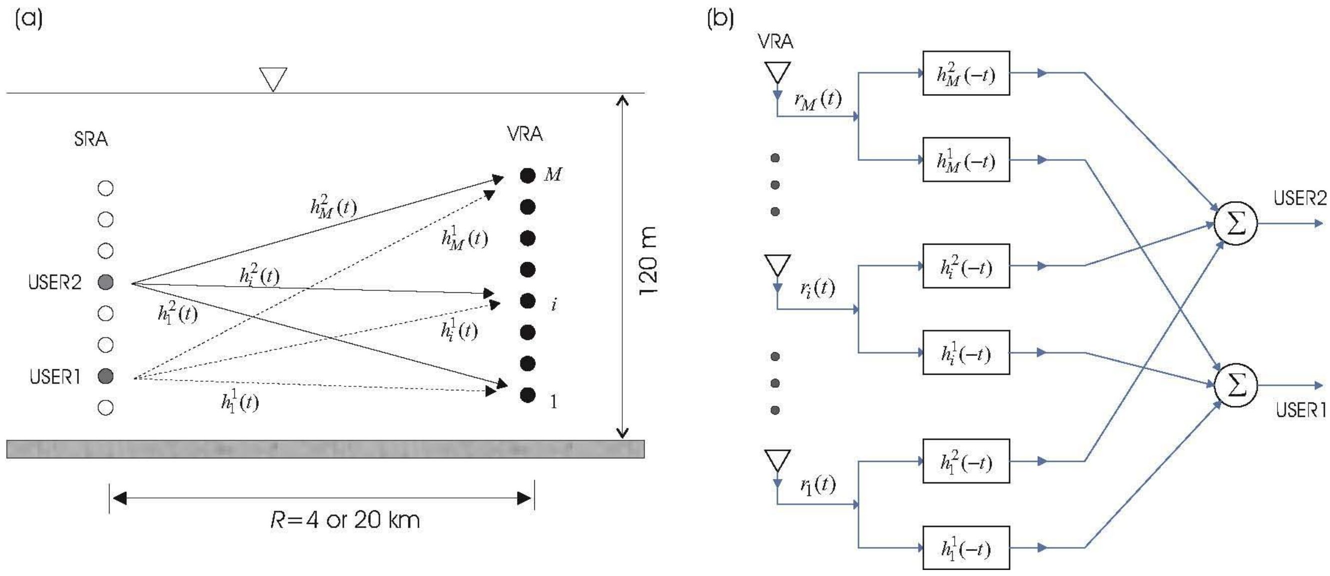

Figure 1. Schematic diagram of multiuser communications using passive time reversal. (a) A subset of element of the SRA are selected as multiple users separated in depth which transmit information to the VRA. The time reversal approach requires knowledge of the channel impulse response $h_i^j(t)$ on the VRA from each user (superscript j). (b) Block diagram for a receiver separating signals from different users in passive time reversal communications. Each user signal after multichannel combining is processed with a single channel decision feedback equalizer (DFE).

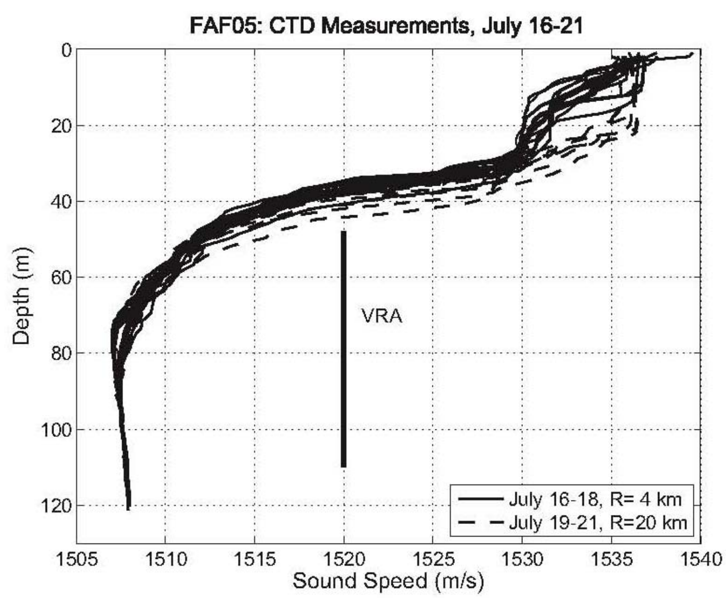

Figure 2. Sound speed profiles measured during the communications transmissions along with an indication of the placement of the VRA in the water column.

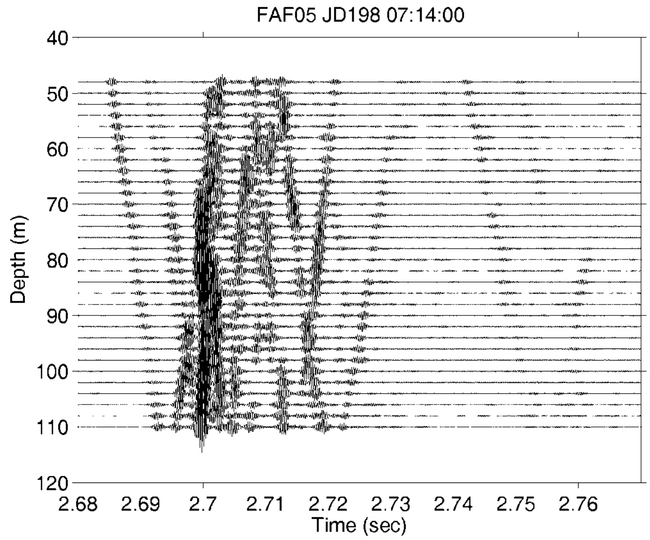

Figure 3. The channel impulse responses observed by the vertical receive array (VRA) from a SRA source at 96 m depth (SRA Ch #7) at 4 km range. The total spread is approximately 90 ms.

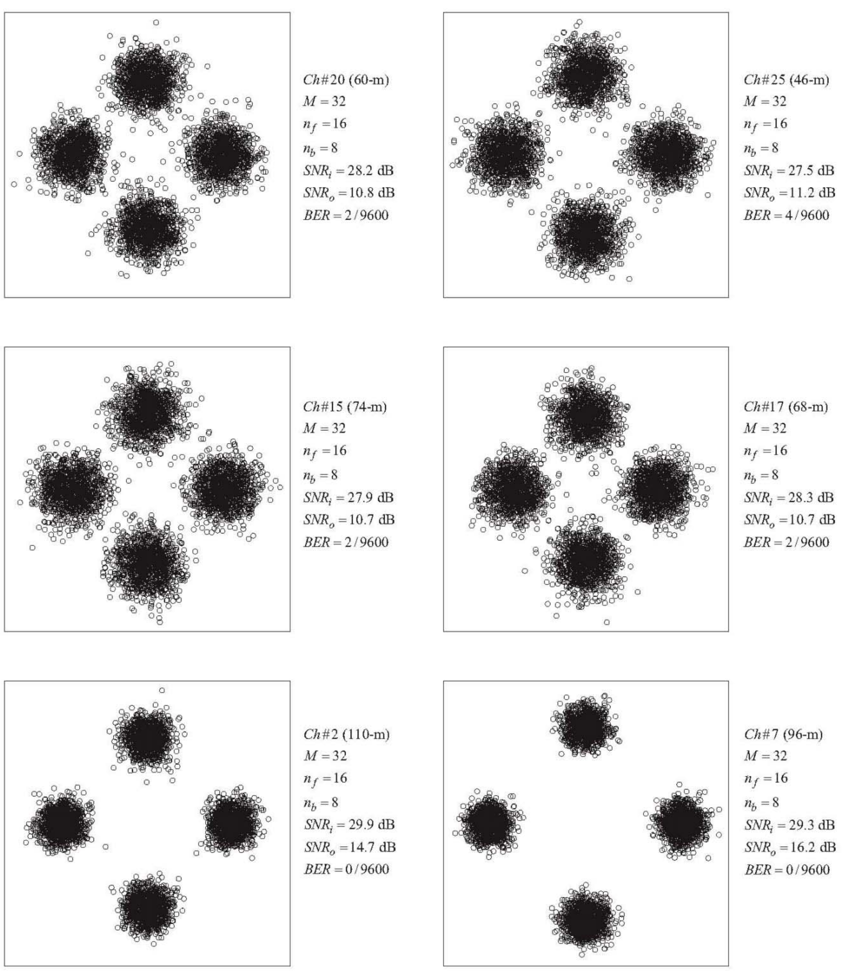

Figure 4. Scatter plots for six users (N = 6) using QPSK: Ch #2 (110 m), Ch #7 (96 m), Ch #15 (74 m), Ch #17 (68 m), Ch #20 (60 m), and Ch #25 (46 m). The aggregate data rate is 6 kbits/s.

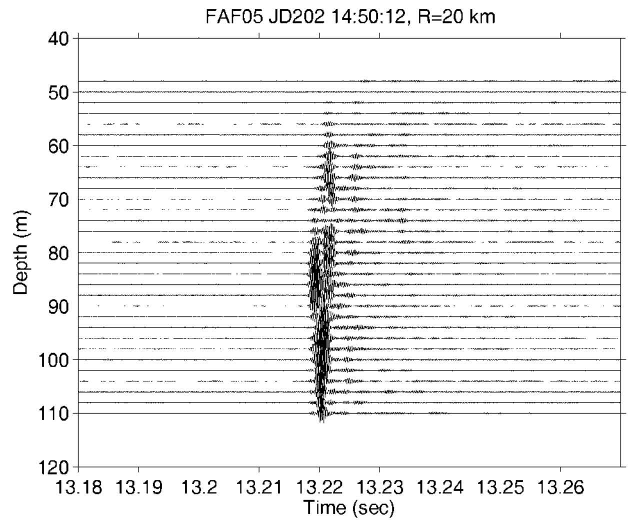

Figure 5. The channel impulse responses observed by the vertical receive array (VRA) from a SRA source at 88 m depth (SRA Ch #10) at 20 km range. The total spread is approximately 20 ms.

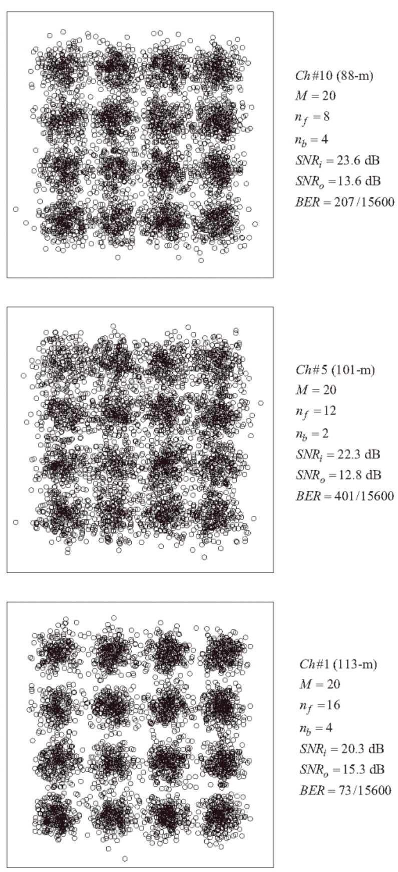

Figure 6. Scatter plots for 3 users (N = 3) using 16 QAM modulation: Ch #1 (113 m), Ch #5 (101 m), and Ch #10 (88 m). The aggregate data rate is 6 kbits/s.